Ocean Surface Wave Optical Roughness: Innovative Polarization Measurement

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LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. The goals of our team are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

The member of the research team are:

- Michael Banner, School of Mathematics, UNSW, Sydney, Australia
- Johannes Gemmrich, Physics and Astronomy, UVic, Victoria, Canada
- Russel Morison, School of Mathematics, UNSW, Sydney, Australia
- Howard Schultz, Computer Vision Laboratory, Computer Science Dept, U. Mass., Mass
- Christopher J Zappa, Lamont Doherty Earth Observatory, Palisades, NY

OBJECTIVES

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure, as is evident in the close range image shown in Figure 1. Traditional descriptors of sea surface roughness are scale-integrated statistical properties, such as significant wave height, mean squared slope (e.g. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and Herbers, 1986). Subsequently, spectral characterisations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al, 2001, Gemmrich et al., 2008) and microscale breaker crest length spectral density (e.g. Jessup and Phadnis, 2005) have been reported.

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Our effort seeks to provide a more comprehensive description of the physical and optical roughness of the sea surface. We will achieve this by implementing a comprehensive sea surface roughness observational 'module' within the RaDyO field program to provide optimal coverage of the fundamental optical distortion processes associated with the air-sea interface. Within our innovative complementary data gathering, analysis and modeling effort, we will pursue both spectral and phase-resolved perspectives. These will contribute directly towards refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

APPROACH

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team (listed above) measuring and characterizing the surface roughness. The group plans to contribute the following components to the primary sea surface roughness data gathering effort in RaDyO:

- polarization camera measurements of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 1), captured at video rates. [Schultz]
- co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]
- high resolution video imagery to record whitecap data, from two cameras, close range and broad field [Gemmrich]
- fast response, infrared imagery to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]
- sonic anemometer to characterize the near-surface wind speed and wind stress [Zappa]

Our envisaged data analysis effort will include: detailed analyses of the slope field topography; laser altimeter wave height and large scale wave slope data; statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the modeling effort will focus on using RaDyO data to refine the sea surface roughness transfer function. This comprises the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as microscale breakers.

WORK COMPLETED

Our effort in FY08 has been primarily in the detailed planning and execution of the suite of sea surface roughness measurements conducted during the Scripps Institution of Oceanography (SIO) Pier Experiment from January 6-28, 2008. This was followed by instrumentation validation, refinements and the necessary logistics in preparation for the first RaDyO field experiment in the Santa Barbara channel during September 5-27, 2008.

In both experiments, from the SIO Pier and from FLIP, we had the responsibility for infrared imagery, laser altimetry, and air-sea fluxes of heat, mass, and momentum as well as radiative fluxes. During FY08, we also refined our data gathering hardware systems and protocols and continued work on analysis techniques for characterizing the various roughness features.

We carried out processing and validation of our infrared gathered at the (SIO) Pier Experiment [January 6-28, 2008] and the infrared and air-sea flux data gathered during the FLIP experiment. These measurements were collocated with our partner investigators' high resolution polarimeteric and optical imaging systems collecting the surface roughness data as well as two lidars mounted in quadrature. We also progressed with our effort to develop a robust 'individual breaker' decomposition capability so that local physical microbreaking elements can be detected and characterized along with their space-time phasing, thereby overcoming the classical Fourier spectrum issue of bound versus free wave contributions in assessing true physical sea surface roughness.

Of major significance to our group's effort was Schultz's successful DURIP application to build a full polarization camera for use in RaDyO. Further details on progress with this development are given in the companion ONR RaDyO Annual Report by Schultz.

In the Santa Barbara Channel experiment Dr. Howard Schultz had the overall responsibility for the Narrow field-of-view Imaging Polarimeter (N-IPol) instrumentation and data processing. Dr. Christopher Zappa installed the N-IPol on FLIP and collected the data. The data processing and analysis will be a collaborative effort between Howard Schultz, Christopher Zappa, Mike Banner, Russel Morison and Larry Pezzaniti (with Polaris Sensor Technologies).

We also updated the data acquisition system consisting of two modules: 1) The sensor package containing a water tight enclosure, pan/tilt head, the IR camera, CameraLink to fiber optic converters, an inertial measurement unit (IMU) for determining the precise orientation of the IR and a digital thermistor; and 2) a portable rack-mountable system containing an interface box, the data acquisition computer, power supplies, and fiber optic to CameraLink converters. The system was designed for efficient deployment aboard FLIP. The system is assembled by mounting the enclosure to the pan/tilt head, connecting the conduit to the sensor package, and connecting the other end of the cabling to the interface box.

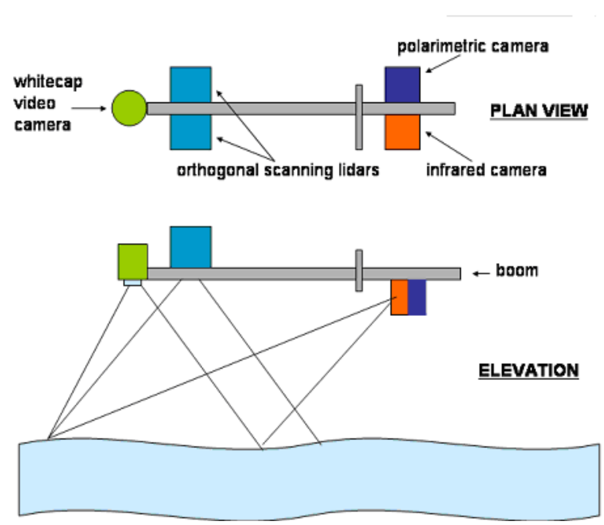

Figure 1. The left panel shows the instrumentation test set-up from the end of the Scripps Pier. The right panel shows a schematic of instrumentation packages deployed. The end of the boom was about 8m above the mean water level. The approximate field of view of the various instruments is shown. Another wide angle whitecap video camera was mounted well above the boom.

Figure 1 below shows the instrumentation deployed in this field testing phase. Banner/Morison deployed two orthogonal line scanning lidars, synchronized for zero crosstalk. These were positioned on the boom so that their intersection point was within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras to measure small-scale surface roughness features and breaking waves. Zappa deployed his infrared/visible camera system (with blackbody target, a blackbody controller, and laser altimeter). The infrared camera was mounted next to the polarimeter and the visible camera was mounted on the end of the boom to collocate the IR, N-IPol, and visible imagery. He also deployed his environmental monitoring system (sonic anemometer, a Licor water vapor sensor, a Vaisala RH/T/P probe, a motion package, a pyranometer, and a pyrgeometer). Gemmrich deployed 2 video visible imagery cameras. One camera was mounted on the main boom next to our other instrumentation packages. The second camera was mounted higher up to provide a wider perspective on larger scale breaking events. Schultz deployed an instrument package located on the boom that includes a polarimetric camera imaging the very small-scale waves. The individual data acquisition systems were synchronized to GPS accuracy which allowed the various data sets to be interrelated to within 0.01 seconds. The IR and N-IPol imagery were triggered at a frame rate of 60 Hz on the same pulse such that their timing synchronization was better than 1 ms.

Figure 2 shows the similar setup during the Santa Barbara FLIP experiment. Note that the N-IPol and IR cameras were offset to account for the difference in nominal incidence angles of 20 for the IR and 35 for the N-IPol.

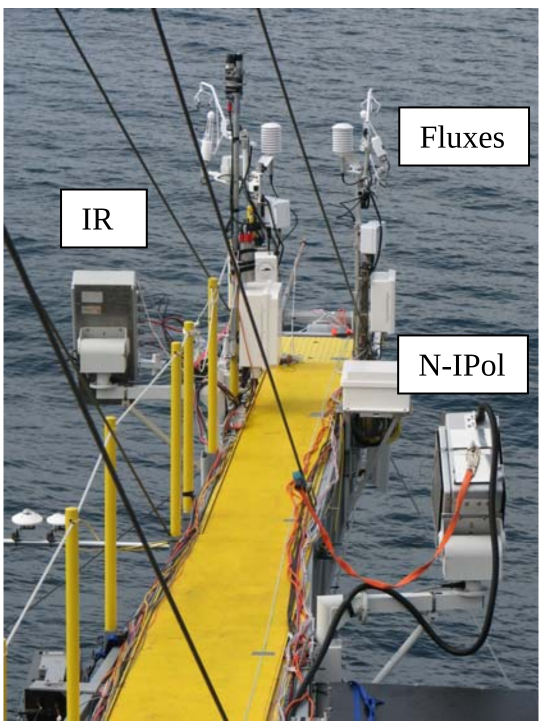

Figure 2. The left panel shows the instrumentation test set-up from the Starboard Boom on FLIP during the RaDyO Santa Barbara Channel Experiment. The visible camera and laser altimeter are located at the end of the boom and not easily visible in this picture. The right panel shows a closeup of the flux instrumentation package deployed. The boom was about 9m above the mean water level. The incidence angles of the IR, visible, and N-IPol cameras as well as the laser altimeter were such that they viewed an overlayed patch of the water surface directly beneath the end of the boom.

RESULTS

Publication of the first manuscript demonstrating the feasibility of the polarimeteric slope sensing technique was completed. The manuscript was published in Measurement, Science and Technology entitled "Retrieval of short ocean wave slope using polarimetric imaging" [*Zappa et al*., 2008].

The primary purpose of the Scripps pier experiment was to prepare for the Santa Barbara and Hawaii FLIP experiments. To meet this goal we identified three tasks: 1) test the new N-IPol recently delivered by Polaris Sensor Technologies, 2) work out the calibration procedure for the N-IPol, and 3) test the synchronization procedures between the infrared imager and the N-IPol data acquisition systems. We were able to recover surface slopes with the new N-IPol instrument and synchronize the Infrared and N-IPol instruments. Figure 3 shows a sample N-IPol intensity image, and x- and y-slope images from the N-IPol with a co-located frame from infrared imager. This example shows the incipient microbreaking that is prevalent at moderate wind speeds. The incipient microbreaker is propagating from top to bottom in the N-IPol imagery and across the IR image from top right to bottom left. Note that the scale of the N-IPol image is the small red inset in the IR image. The IR image shows the disruption of the surface skin layer that defines microbreaking waves and is directly related to the complicated slope features observed in the N-IPol. These slope features are characterized by steep slopes that also have high spatial variance that exhibits a dimpled structure observed previously in the laboratory by *Zappa et al*. [2004].

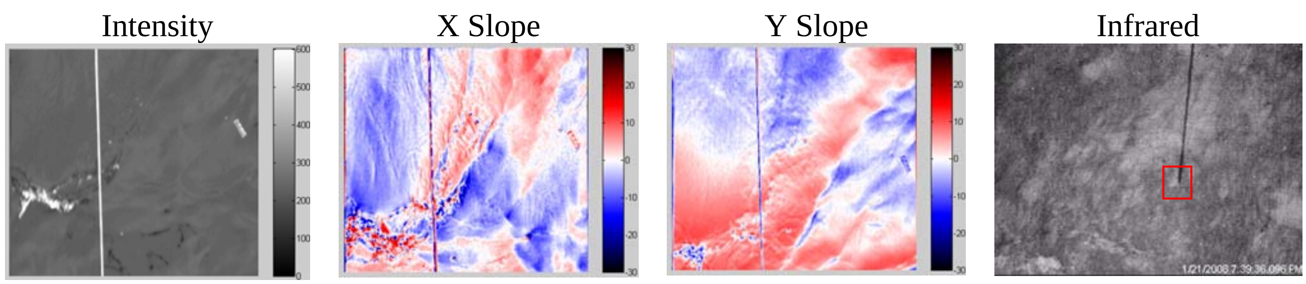

Figure 3. A sample of an intensity image, x and y-slope images and an infrared image. The line in the center is a cable extending from the boom to the water surface. The inset red box in the IR image shows the overlay of the N-IPol image. The IR image shows the incipient disruption of a microscale breaking wave.

Our complete system was field-deployed from FLIP during the first intensive observational experiment during September 2008 in the Santa Barbara channel. Our systems included infrared/visible imagery, laser altimetry, and air-sea fluxes of heat, mass, and momentum as well as radiative fluxes. A wide range of conditions prevailed where the wind speed, U_{10}, ranged from light and variable, up to 12 m/s and the significant wave height ranged from 0.7 m to 2.0 m. Figure 4 below shows a summary of the wind speed and wave heights measured during. The instruments were deployed from a boom at a height of ~9m above the mean sea level. The data show a distinctive and persistent diurnal structure to the wind speed that was stronger in the afternoon relative to in the morning. The laser altimeter operated better in the strong wind forcing conditions, as expected, where the increase in specular surface facets provides more comprehensive return for the time-of-flight measurement. Our experience confirmed that this method will provide useful data on the height of the dominant waves.

This information characterizes the background environment experienced by the short wind waves (the sea surface microstructure roughness) measured by the IR and N-IPol imagery.

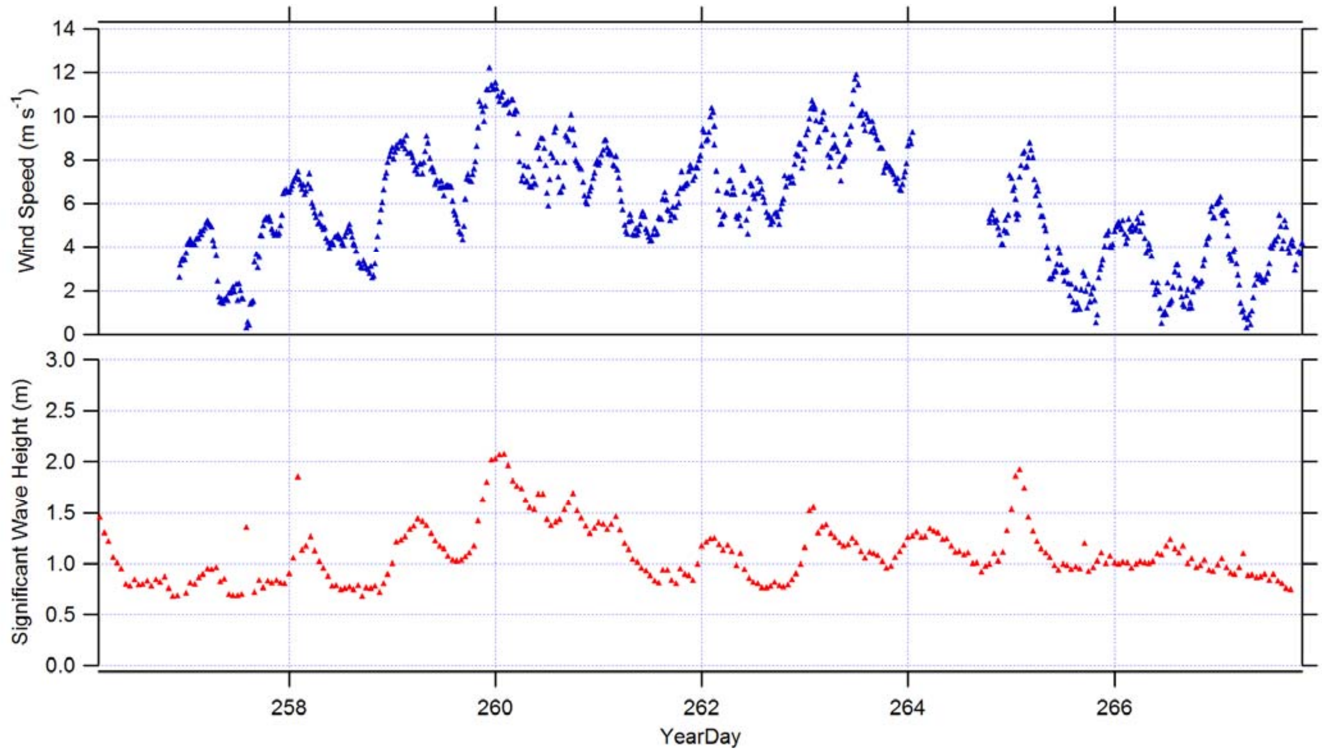

Figure 4. Time series of the wind speed (sonic anemometer) and significant wave height (laser altimeter) during the RaDyO Santa Barbara Channel Experiment aboard the R/P FLIP. The measurements were made from the starboard boom at a nominal height of roughly 9 m.

IMPACT/APPLICATIONS

This effort will provide a far more detailed characterization of the wind driven air-sea interface, including wave breaking (whitecaps and microscale breaking). This is needed to provide more complete parameterizations of these processes, which will improve the accuracy of ocean optical radiative transfer models and trans-interfacial image reconstruction techniques.

RELATED PROJECTS

The results and publication here led to a DURIP award ("Equipment in Support for Polarimetric Imaging," PI: Dr. Howard Schultz, Award Number: N00014-07-1-0731) for a PSS system that will spark a new class of instrumentation that will benefit a wide variety of oceanography and fluid mechanics research and educational programs. The DURIP will contribute PSS directly towards our effort within the ONR RaDyO DRI scheduled for FY07-10 and will provide a much-needed refinement in the representation of surface wave distortion in present air-sea interfacial optical transmission models.

The work here is a direct follow-on from the Waves, Air-Sea Fluxes, Aerosols, and Bubbles (WASFAB) experiments in 2005 at the FRF pier in Duck, NC. The results from WASFAB will directly augment the capabilities for quantification of the distribution of microscale wave breaking and whitecapping in the understanding of air-sea interaction.

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PUBLICATIONS

Christopher J. Zappa, Michael L. Banner, Howard Schultz, Andres Corrada-Emmanuel, Lawrence B. Wolff & Jacob Yalcin (2008) "Retrieval of short ocean wave slope using polarimetric imaging," Measurement Science and Technology, 19, 055503, doi: 10.1088/0957-0233/19/5/055503. [Published, Refereed]